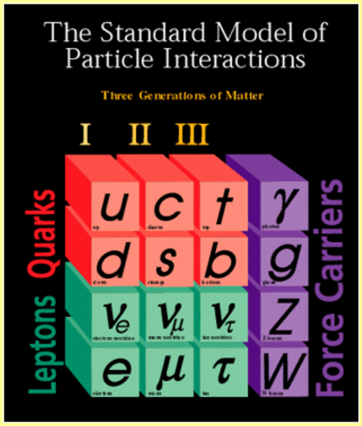
Parity Nonconservation and the Standard Model:




Weak force carriers, W+, Z°, W- have spin 1 (bosons) and are left-handed, i.e. they have h = -1 always (spin opposite to direction of motion)

If this is the case, then parity violation in the weak interaction is a "built-in" feature.

But nobody knows why....

Extensive searches for physics "Beyond the Standard Model" probe the existence of a symmetric set of right-handed force carriers.

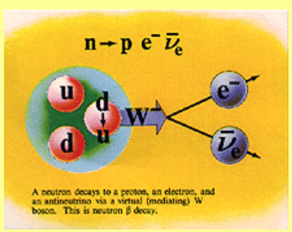
None detected yet, but if they exist, they are required to be extremely heavy!

Neutrinos: $\nu_e$ etc. have negative helicity; antineutrinos have positive helicity!

Many precise experimental tests are in agreement with this picture – see the particle data group web page for a current summary. High energy collider experiments have played a major role in discovering the heavier quarks and members of the lepton family...

---

How do we know that the weak interaction model is correct? 



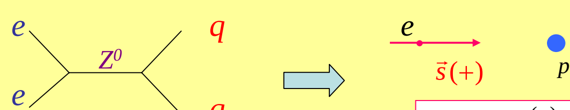
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

The picture of short-range, heavy charged force carriers gives a mechanism for nuclear beta decay that is consistent with older theories and experimental data.

.. but if the W- only travels 0.002 fm at the speed of light, how do we know it is there? ......

The neutral weak force carrier $Z^0$ is not required to explain beta decay, but is predicted to be a 'heavy cousin' of the photon, and the mediator of 'neutral' weak interactions – something that was not foreseen prior to the development of the current "electroweak" interaction theory by Glashow, Weinberg & Salaam – Nobel prize 1984.
http://nobelprize.org/physics/laureates/1984/index.html

Immediate consequences: e.g. parity violating (PV) electron scattering, now a standard tool for nuclear and particle physics (e.g. $Q_{weak}$ experiment: http://www.jlab.org/qweak/ )



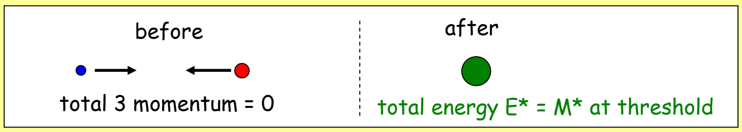

$$PV: \quad A = \frac{\sigma(+) - \sigma(-)}{\sigma(+) + \sigma(-)} \cong -10^{-5}\, Q^2\, (GeV^2) \;+\; O(Q^4)$$

## Direct evidence: creation of weak force carriers in colliding beam experiments

3

consider first a fixed-target experiment: extra kinetic energy in the beam is "wasted" rather than used for new particle production, since momentum has to be conserved (forward direction)


minimum energy to produce M* corresponds to zero kinetic energy in the center of momentum frame:




write down total 4-momentum in both lab and CM frames:

lab: $P_\mu = (\vec{p}, i(E+M))$ CM: $P'_\mu = (0, iE^*)$

## Now work out how much beam energy is needed in the lab:

4

TRICK: length[2] of a 4 vector is invariant!!!

lab CMS

$$P^2 = (P')^2$$

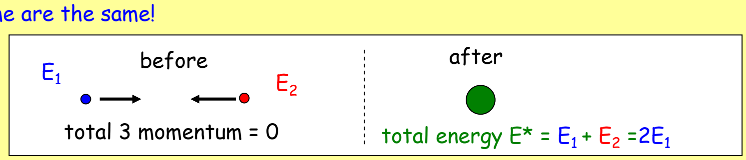
$$\Rightarrow \ p^2 - (E+M)^2 = -(E^*)^2$$

$for \ \ m_{beam} << E \quad ie \ \ relativistic \ beam, \ (approx.) \ then$

$$\Rightarrow \ E^* = \sqrt{2ME + M^2}$$

Available energy to make new particles goes up as the square root of the beam energy

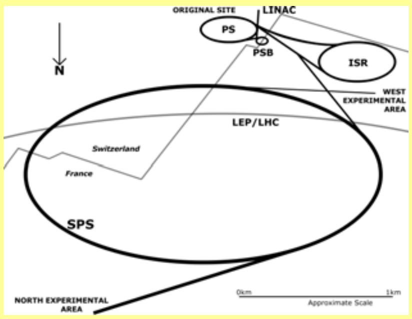
Now consider a colliding beam experiment – for simplicity, take equal mass particles eg. e+ and e- as used at the LEP collider at CERN. Then the LAB frame and the CM frame are the same!

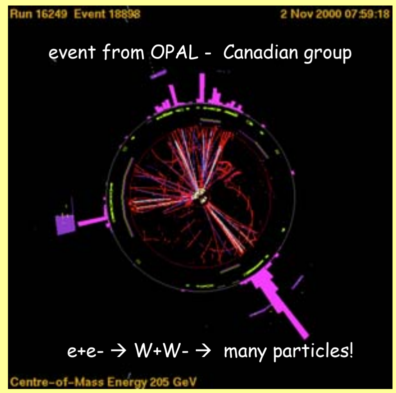



Available energy to make new particles goes up linearly with beam energy → more efficient!

CERN Accelerator Complex – 27 km long, under the city of Geneva, Switzerland! 5

several international collaborations built sensitive "calorimeter" and tracking detectors to record final state particles produced in high energy e+ e- collsions to search for new particles at LEP (now decommissioned to be replaced by the LHC or "Large Hadron Collider")



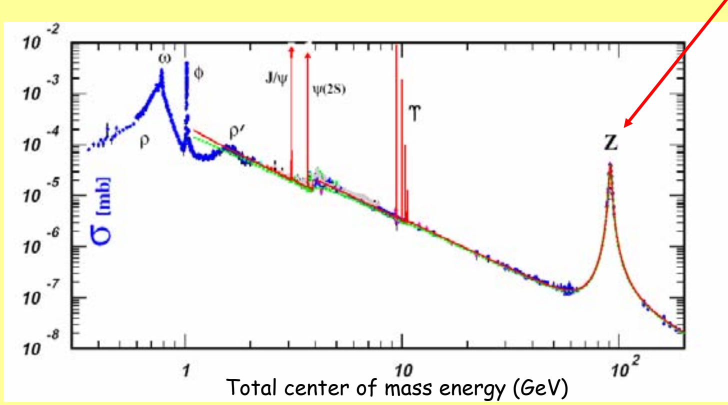

Particle Data Group: cross section for e+e- annihilation at high energy 6

- resonance peaks for production of neutral particles – meson resonances seen at lower energy. All of these have J = 1, negative parity (recall pion has J = 0)

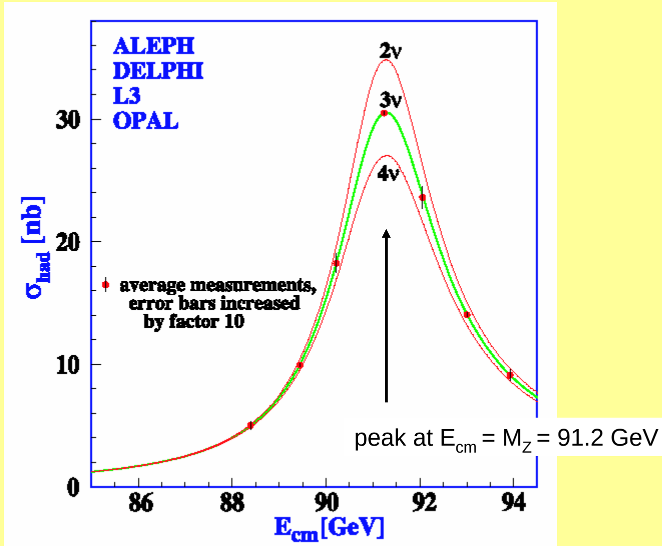
$$\rho = \frac{1}{\sqrt{2}}(u\bar{u} - dd) \quad T = 1 \qquad \omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}),\ T = 0$$

$$\phi = s\bar{s} \qquad J/\psi = c\bar{c} \qquad \Upsilon = b\bar{b}$$

Z boson, discovered 1983, CERN



Close up of Z resonance peak gives the mass of the Z and the number of neutrinos! 7

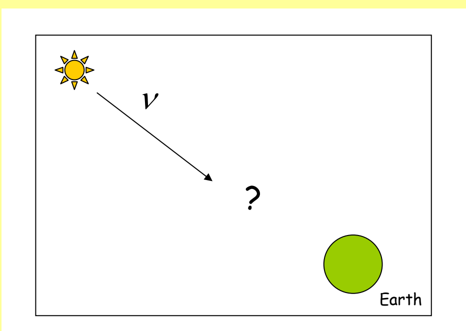



(N = 3 looks pretty good!)

Fit gives N = 2.994 +/- 0.012 neutrino types!

And FINALLY, a quick word about SNO: 8

Sudbury Neutrino Observatory: http://www.sno.phy.queensu.ca/




- SNO was built over a decade starting in the late 1980's at a cost of ~ $100M to solve a long-standing problem in the observed deficit of neutrinos coming from the sun.
- A classic radiochemical experiment by Ray Davis et al carried out in a gold mine in South Dakota using the reaction:

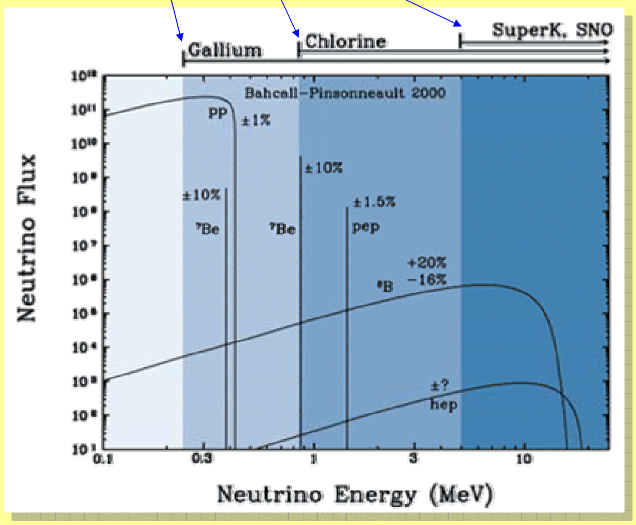
$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

had reproducibly detected only about 1/3 of the expected number of neutrinos of solar origin. What was wrong???

Prior to SNO, several other solar neutrino experiments were constructed and in operation world wide, e.g. the Kamiokande detector in Japan, SAGE and GALLEX detectors in Europe ... all had slightly different energy sensitivities and operated using different reactions to detect the neutrinos, but all found a discrepancy in the solar flux!

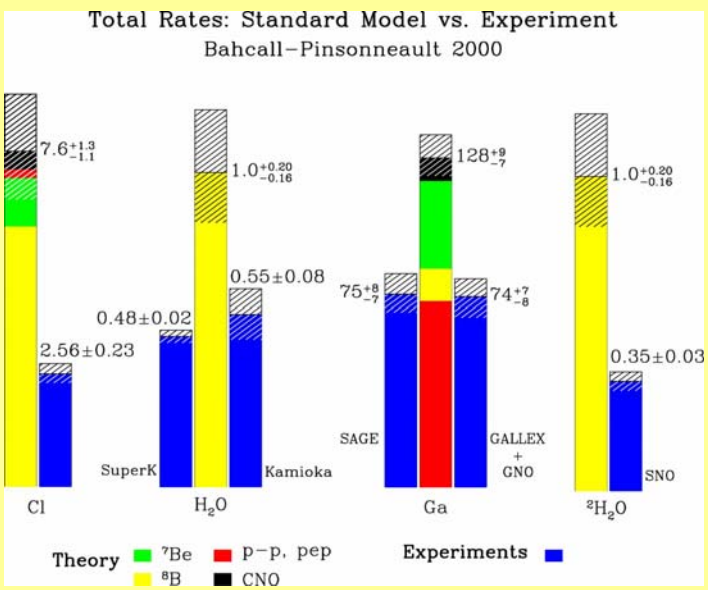
Calculated neutrino flux from fusion reactions in the sun, J. Bahcall et. al 9

Energy thresholds of various detectors are shown:




Ref: Williams, section 14.7

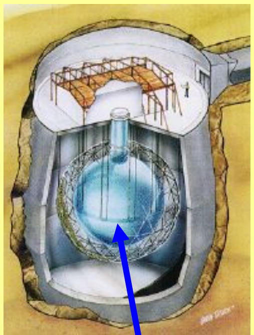
All detectors, including SNO, show a deficit of electron neutrinos from the sun: 10

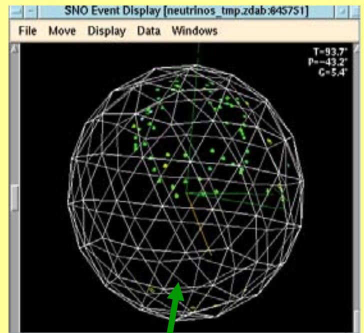


## SNO – a unique $D_2O$ Cerenkov detector that can "see" all neutrino types



4700′ underground in the Creighton nickel mine in Sudbury, Canada, to suppress background from cosmic ray muons, etc:






acrylic vessel holds 1000 tonnes of heavy water, $D_2O$ that makes an ideal detector for neutrinos.

20" diameter photo-multiplier tubes looking inward detect Cerenkov light when a neutrino interacts in the water

Neutrino candidate event: Cerenkov "ring" on one side of the detector with nothing entering from the other side.

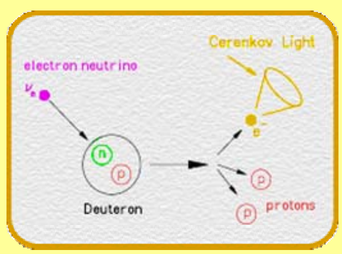
## Neutrino detection mechanisms in heavy water:

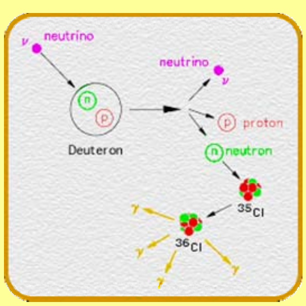


1. "Charged current" mechanism:

$$\nu_e + d \rightarrow p + p + e^-$$

(electron produces Cerenkov light in the water tank)




2. "Neutral current" mechanism:

$$\nu + d \rightarrow n + p + \nu$$

resulting neutron can be captured in a salt solution, and resulting $\gamma$-rays, which hit electrons in the water, again produce Cerenkov light that is picked up in the PMT's

Ratio of 1 : 2 gives the ratio of electron-type to total neutrinos from the sun!

SNO published results: http://www.sno.phy.queensu.ca/sno/publications.html 13

$$\Phi_{CC} = 1.76 \pm 0.05 \pm 0.09 \cdot 10^{6}\,\mathrm{cm}^{-2}\,\sec^{-1}$$

electron-neutrinos only

$$\Phi_{NC} = 5.09\ {}^{+0.44}_{-0.43}\ {}^{+0.46}_{-0.43} \cdot 10^{6}\,\mathrm{cm}^{-2}\,\sec^{-1}$$

all neutrino types

Ratio: $$\frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} = 0.35$$

Significance of the SNO result: first experiment to "see what happened" by measuring all neutrino types

Interpretation:

- the total number of neutrinos is consistent with expectations from the solar model.
- only electron-type neutrinos are produced in solar fusion reactions
- 2/3 of these must be turning into other neutrino types ($\mu$, $\tau$) before reaching earth!

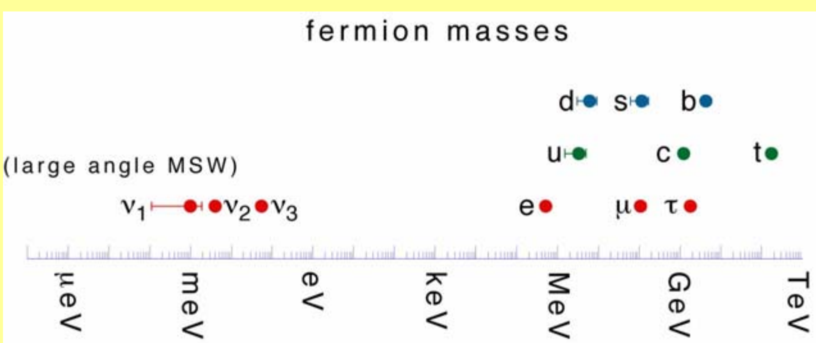
Unavoidable conclusion: neutrinos must have a small but finite rest mass! (next question: how big is it?)

Neutrino masses and mixing: (see, e.g. http://www.sns.ias.edu/~jnb/ ) 14

The theory of neutrino mixing gets complicated very quickly, but in a nutshell, the observation of "neutrino oscillations" sets limits on the mass-difference $\Delta m^2$ and the mixing angle $\theta$, e.g. for only two neutrino types, one could write:

$$|\nu_e(t=0)\rangle = \sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Then as time evolves, with the masses of 1 and 2 being different, the observed "neutrino state" will be a different linear combination of 1 and 2 that depends on the parameters $\Delta m^2$ and $\sin^2\theta$ . Combined data from all experiments can be used to place limits on the mixing parameters.... so far, the favoured situation looks like this:



The SNO result is an incredible achievement for physics and Canada 15

http://www.nserc.ca/news/2003/p031124.htm

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada | Canada

Français | Contact Us | Help | Search | Canada Site

Home NSERC Prizes | Program Guides | Program News | On-line Services | Funding Decisions

## Leader of Sudbury Neutrino Observatory Wins Top Canadian Science Prize

**Ottawa, Ontario, November 24, 2003** – Arthur McDonald was today named winner of the 2003 Gerhard Herzberg Canada Gold Medal for Science and Engineering.

The prize guarantees that Dr. McDonald, a professor at Queen's University, will receive $1 million in research funding from the Natural Sciences and Engineering Research Council (NSERC).

"Dr. McDonald was the driving force for the Sudbury Neutrino Project, which has been such an outstanding international scientific success story and a source of great pride for all Canadians," said Ottawa-Vanier M.P. Mauril Bélanger, who announced the award on behalf of

It wasn't easy! For a few years, the subatomic research community almost went broke trying to pay for SNO .... but it was worth it!

*SAP visits SNO as chair of NSERC GSC, 1997 – borrows $3M from NSERC to pay for construction cost overrun....*